Final Report of AOARD 11-4069

Title: Modeling of Klein tunneling for electron field emission from graphene

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Since the discovery of large size graphene in 2004, it has initiated very active research activities in understanding the unique electronic properties of graphene, including high carrier mobility, ballistic transport, and linear light-like energy dispersion relationship. Promising applications include field effect transistors, sensors, spintronic devices, and many others in nanoelectronics. In recent experimental papers, graphene has shown its potentials to be an electron source in vacuum electronics. Practical applications include being an efficient emitter for display backlight sources like LCD and LED, or even as the active emitters for field emitter flat panel display like carbon nanofibers and carbon nanotubes. If the emitted current density can be improved to high current regime, it can be also used as intense electron source for high power microwave source.

In this report, we will present the results and outcome of works funded in this grant:

Topic 1: Shot noise of low energy electron field emission due to Klein tunneling

In this topic, we have extended our prior works done in phase 1 published in the journal of APL 99, 093112 (2011) in order to study the shot noise of electron field emission due to Klein tunneling. The results was published in the following paper

- S. Sun, and **L. K. Ang**, "Shot noise of low energy electron field emission due to Klein tunneling", **J Appl. Phys.** 112, 016104 (2012).

In our model, we use two different methods (relativistic WKB and transfer matrix) to calculate the transmission coefficient and thus obtain the Fano factor (γ or suppression of shot noise) as a function of temperature T, Fermi energy E_f , and local electric field F. The comparison between two methods shown pretty good agreement as shown in Fig. 1.

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14. ABSTRACT
Since the discovery of large size graphene in 2004, it has initiated very active research activities in understanding the unique electronic properties of graphene, including high carrier mobility, ballistic transport, and linear light-like energy dispersion relationship. Promising applications include field effect transistors, sensors, spintronic devices, and many others in nanoelectronics. In recent experimental papers, graphene has shown its potentials to be an electron source in vacuum electronics. Practical applications include being an efficient emitter for display backlight sources like LCD and LED, or even as the active emitters for field emitter flat panel display like carbon nanofibers and carbon nanotubes. If the emitted current density can be improved to high current regime, it can be also used as intense electron source for high power microwave source.

15. SUBJECT TERMS
Klein Tunneling, Graphene, Electron Source, High Power Microwave Source

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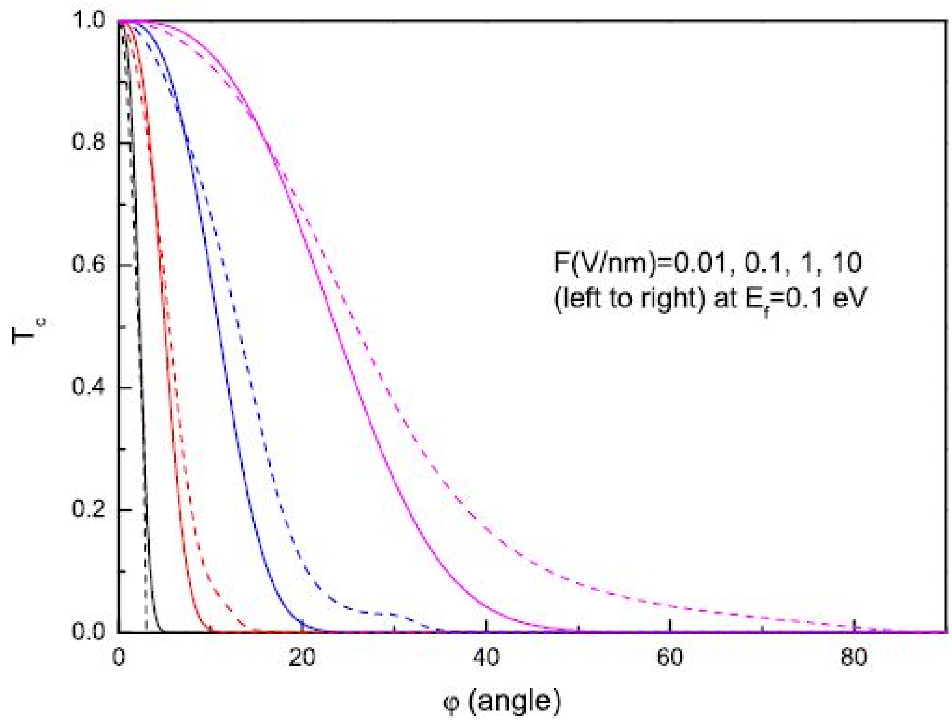

FIG. 1. Transmission coefficient T_c computed by using the relativistic WKB method (solid line) and the transfer matrix method (dash line). From left to right, F (V/nm) $= 0.01, 0.1, 1$, and 10 at $E_f = 0.1$ eV.

It is found that a universal maximum value of about γ = 1/3 can be reached at low temperature limit within a certain range of local electric fields. In Fig. 2 and 3 below,

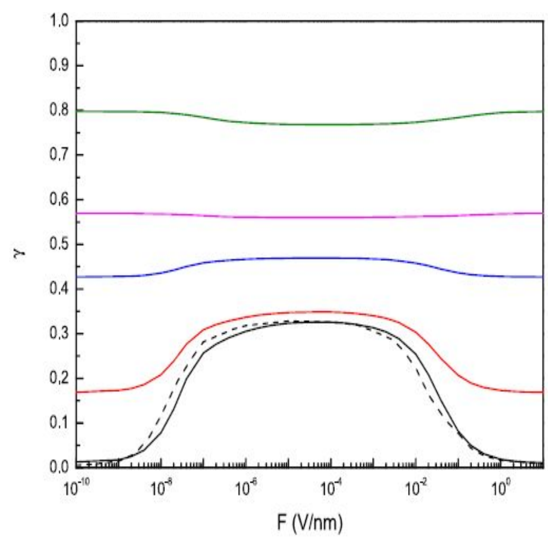

FIG. 2. The Fano factor γ as a function of the local electric field F at various temperatures T (K) = 5, 100, 300, 500, and 1000 (bottom to top, solid lines) at $E_f = 0.1$ eV. The dashed line is the result computed by using the transfer matrix method at $T = 5$ K and $E_f = 0.1$ eV.

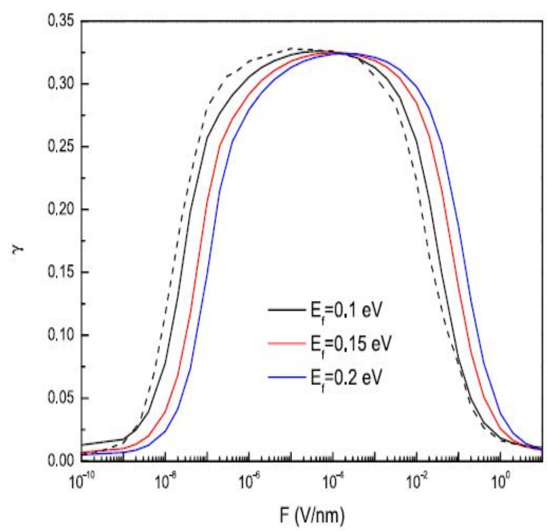

FIG. 3. The Fano factor γ as a function of the local electric field F at various Fermi energies E_f (eV) = 0.1, 0.15, and 0.2 (left to right, solid lines) at $T = 5$ K. The dashed line is the result computed by using the transfer matrix method at $T = 5$ K and $E_f = 0.1$ eV.

Topic 2: Over barrier electron emission using graphene using a time varying potentials

We had proposed a model which describes side-band electron emission from vertically aligned monolayer graphene with an internal time-oscillating barrier and a static edge barrier. Our results show that electron emission is governed by the over-barrier emission process, which is dominated by the time-oscillating barrier. The emitted current line density J [nA/nm] is only dependent on the amplitude and on the frequency of the time-oscillating barrier, which is characterized by $0 < \gamma = V_1 / h\omega < 1$ as shown in Fig. 4 below.

Note this topic has attracted international attention that the PI has given an invited oral talk in the 2013 International conference on vacuum electronics at Pairs. The results have been published in

- Shijun Liu, and L. K. Ang, "Over-barrier side band electron emission from graphene with time-oscillating potential", **Carbon** 61, 294-298 (2013).

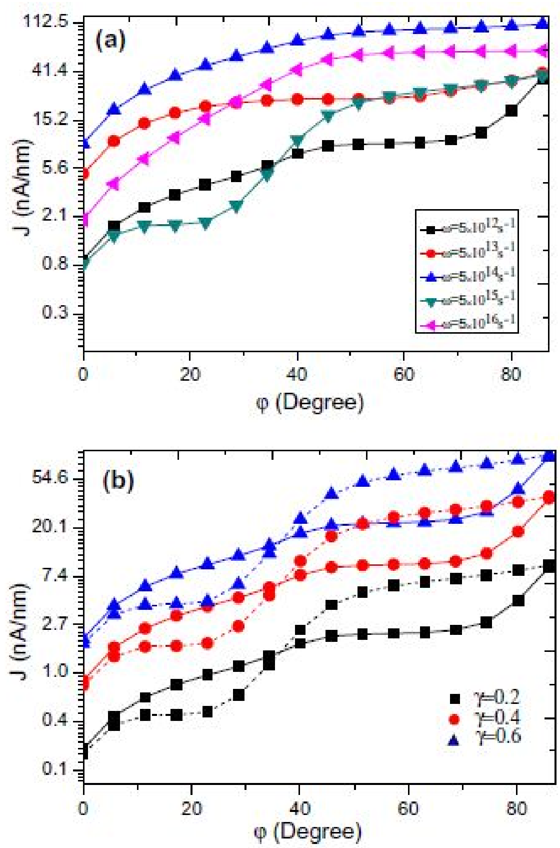

Fig. 4: The emission current line density J [nA/nm] as a function of incident angle for (a) different frequency ω at $\gamma = V_1 / h\omega = 0.5$; and (b) different γ at ω [rad/s] = 5×10^{15} (dashed lines) and 5×10^{12} (solid lines).

In our calculation, we also confirm it is indeed an over barrier emission that the electron emission is not sensitive to the surface barrier as shown in fig. 5 in using two types of image charge potential.

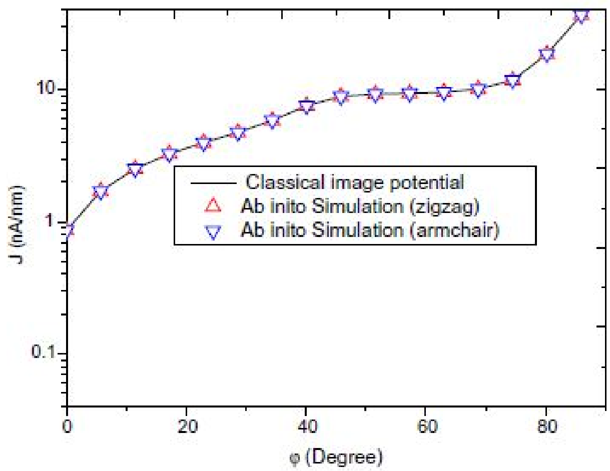

Fig. 5: A comparison is made between our results (solid) with ab initio simulation results (symbols).

Topic 3: Ultrafast excited electron emission from metal tips

Other than the electron emission from graphene, we have emission, we also study if the electron emission is correct at femtosecond time scale. For simplicity, we focus on metal tip, and found that we will need 2 photon absorption instead of 3 photon absorption predicted by Einstein generalized photoelectric effect, if the pulselenght of the laser is reduced down to 8 fs or smaller as shown in Fig. 6

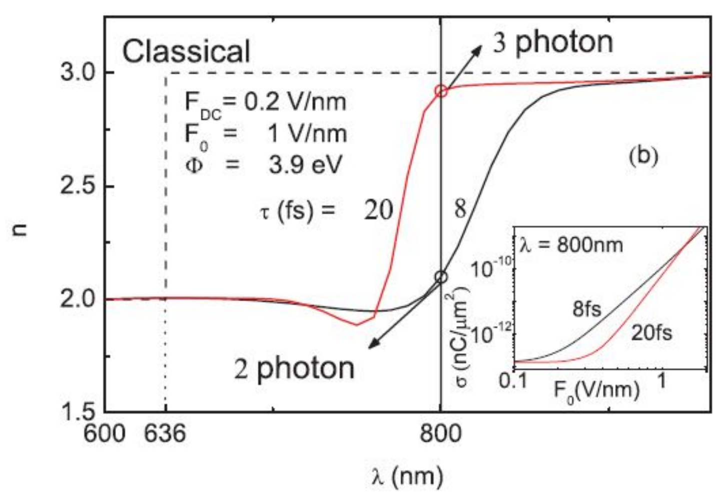

Fig. 6: Dependence of n on laser wavelength λ atdifferent pulse lengths τ . The vertical line shows the transition from n = 3 (τ = 20 fs) to n = 2 (τ = 8 fs).

This paper was first published in PRB and later also an invited paper in Physics of Plasmas (as the PI was an invited speaker in the 2012 APS DPP annual meeting in USA]

- M. Pant, and **L. K. Ang**, "Ultrafast laser induced electron emission from multiphoton to optical tunneling", **Phys. Rev. B** 86 045423 (2012).

- **INVITED** (APS-DPP12): **L. K. Ang**, and M. Pant, "Generalized model for ultrafast laser induced electron emission from a metal tip", **Physics of Plasmas** 20, 056705 (2013).

Topic 4: Novel Scaling Laws for the Langmuir-Blodgett Solutions in Cylindrical and Spherical Diodes

Recently, we also work with our USA collaborators Prof. Y. Y. Lau from U of Michigan in developing new models of SCL current in cylindrical and spherical diodes. The paper was published in the PRL paper below

- Y. B. Zhu, P. Zhang, A. Valfells, **L. K. Ang**, and Y. Y. Lau, "Novel scaling laws for the Langmuir-Blodgett solutions in cylindrical and spherical diodes", **Phys. Rev. Lett.** 110, 265007 (2013).

In Fig. 7, we provide for the first a semi-analytical formula that is able to reproduce the LB results over the entire range of reported values.

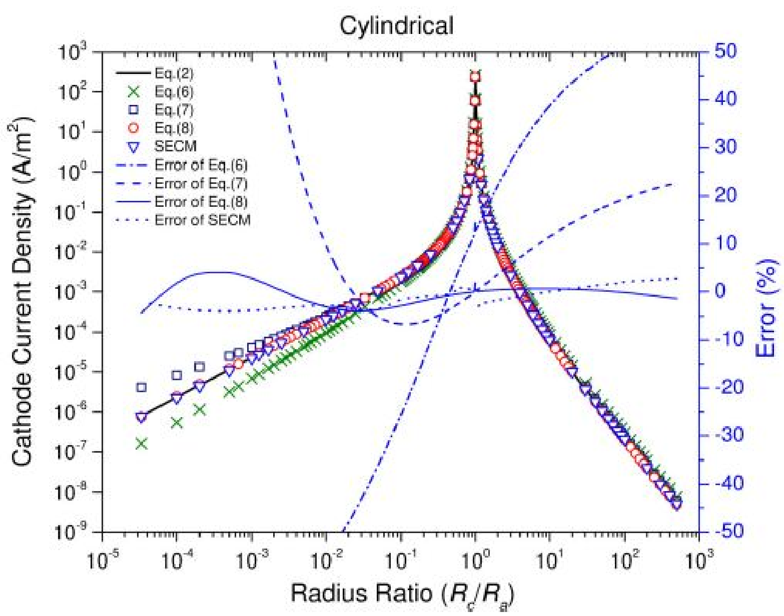

Fig. 7 Comparison between the LB law (solid line) and its various approximations for a cylindrical diode over a wide range of Rc=Ra.

Summary

At the end of this project, we have learned of great research interests of field emission from graphene and ultrafast laser induced electron emission from metal tips resulted our works. We are now in the process of combining our expertise (ultrafast laser induced emission and electron emission from novel materials) for the following topics for AOARD future funding that has been submitted as a white paper.

Modeling of ultrafast laser induced emission from Topological Insulator and Graphene